Particle Production and Propagation in Nuclei

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an Overview of
mostly $e\text{-}A \to h + X$

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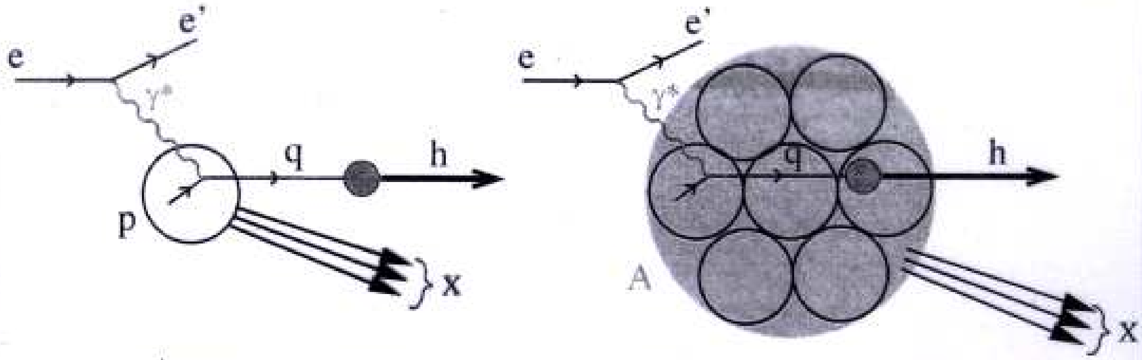
Is the nucleus just a "sum" of protons and neutrons?



a) $e\ p \longrightarrow h\ X$ b) $e\ A \longrightarrow h\ X$

If so, in DIS the photon would only see a bigger target, but the same number of hadrons *per scattered electron* would be produced:

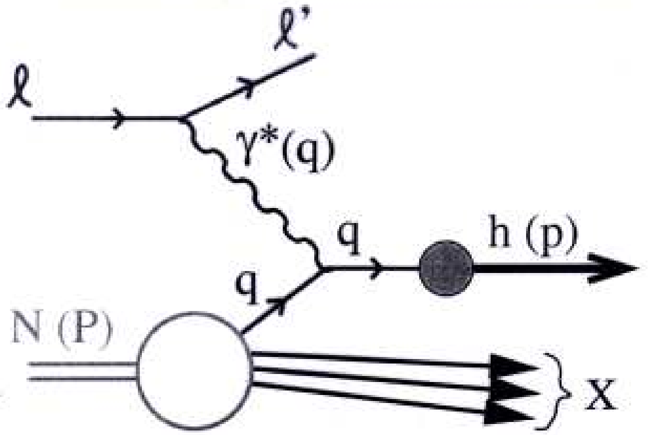
$$\frac{1}{N_A^\ell}\frac{dN_A^h}{dz} = \frac{1}{N_D^\ell}\frac{dN_D^h}{dz} \times \boxed{R_M^h(z)}$$
$$\text{with } \boxed{R_M^h(z) = 1}.$$

BUT experimentally: $R_M^h(z) \neq 1 \Longrightarrow$ NUCLEAR EFFECTS

What is changing inside the nucleus?

- ⇝ virtual photon penetration in the nucleus?
- ⇝ quark composition of the nucleons? √
- ⇝ struck quark propagation?
- ⇝ hadron creation process? √
- ⇝ hadron propagation (nuclear absorption)? √

DIS and hadron production



KINEMATIC VARIABLES

$$x = \frac{-q^2}{2q \cdot P} = \frac{Q^2}{2M\nu}$$
$$\nu = \frac{q \cdot P}{\sqrt{P^2}} = E_\ell - E'_\ell$$
$$z = \frac{q \cdot p}{q \cdot P} = \frac{E_h}{\nu}$$

$$Q^2 = -q^2 = 2Mx\nu$$

Experimentally

Hadron production presented in terms of the *multiplicity ratio*

$$R_M^h(z) = \frac{1}{N_A^\ell}\frac{dN_A^h}{dz} \Bigg/ \frac{1}{N_D^\ell}\frac{dN_D^h}{dz}$$

Experiments: $R_M^h(z) \neq 1 \Longrightarrow$ NUCLEAR EFFECTS

Theoretical models

- nuclear absorption Bialas & Chmaj '83, Bialas & Gyulassy '87
- gluon-bremsstrahlung model Kopeliovich et al. '95
- higher-twist effects Guo & Wang '00, Qiu & Sterman '01, Wang^2 '02
- rescaling models

Speculation about Higher twist Effect

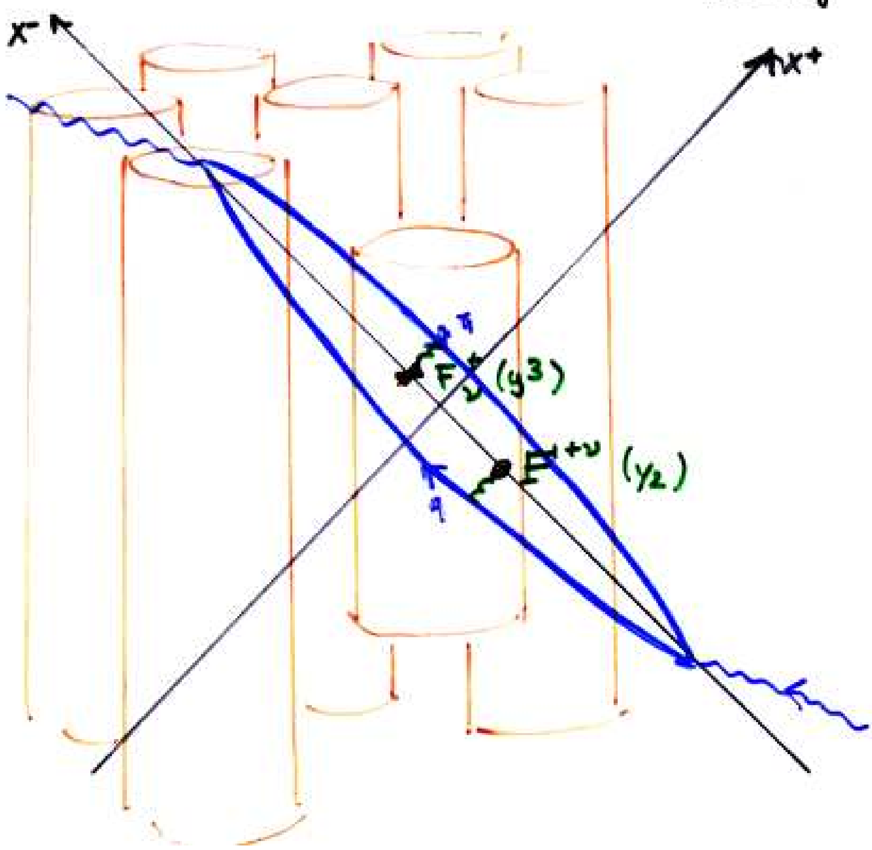
from q-Gluon correlations (G. Sterman et al.)
(PRD 50 (1994) 1951, J. Qiu & G. Sterman hep-ph/9610476)

$$f_{qG}(x_1, x_2, x_3) = \int \prod_i \left(\frac{dy_i}{2\pi}\right) \quad e^{ip^+ \Sigma x_i y_i}$$

$$\langle A(p) | \bar{q}(y_3)\, \gamma^+ F^{+\nu}(y_2)\; F^{+}_{\nu}(y_3)\; q(0)\, | A(p) \rangle$$

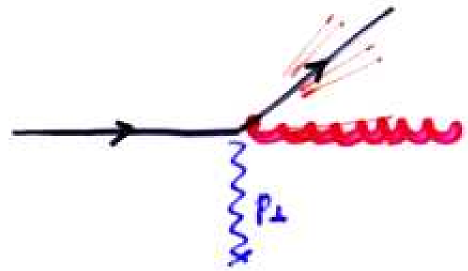
$$\Longrightarrow \quad \langle k_\perp^2 \rangle_A = \langle k_\perp^2 \rangle_N + \quad \lambda^2 A^{1/3}$$

$\lambda^2 \simeq 0.2\ \mathrm{GeV}^2$
(Milana hep-ph/9309328)
X.N. Wang PRL 77 (1996))



Bethe-Heitler Scattering Cross sections

(B. Kopeliovich)
(U. Wiedemann)
(Arleo)



Induced gluon Radiation $\omega, \vec{k}_\perp$

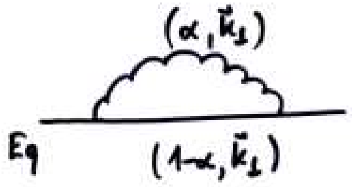
$$\frac{dn}{d\omega\, d^2k_\perp} \simeq \frac{3\alpha_s(\vec{k}_\perp^2)}{\pi^2}\,\frac{1}{\omega}\,\frac{\vec{p}_\perp^{\,2}}{\vec{k}_\perp^2\,(\vec{k}_\perp^2-\vec{p}_\perp^{\,2})^2}$$

$$\frac{dE_{\text{loss}}}{dz} = -\frac{d}{dz}\int d^2k_\perp \int^{\text{Cut}(z)} \omega\, d\omega\, \frac{dn}{d\omega\, d^2k_\perp}$$

length

Time to separate gluon from quark : $\Delta T_s = z_s/c$

$$\frac{1}{\Delta T_s} = \frac{k_\perp^2}{\alpha(1-\alpha)\,2E_q} \underset{\alpha \ll 1}{\approx} \frac{k_\perp^2}{2\omega} = \frac{1}{z}$$

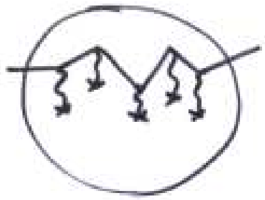


Cut-off ω energy (z) : $\quad \omega = \dfrac{z\,k_\perp^2}{2} = \text{Cut}(z)$

$$\frac{dE_{\text{loss}}}{dz} \simeq \frac{3}{\pi^2}\,\langle \vec{p}_\perp^{\,2}\rangle \ln \langle \alpha_s(p_\perp)\rangle \;; \qquad (k_\perp^2 \lesssim p_\perp^2)$$

$\uparrow$

$\langle p_\perp^2 \rangle \sim$



$$= \langle p_\perp^2 \rangle_0 \frac{z}{\lambda} ;$$

$$\lambda = \text{m.f. path} = \frac{1}{\text{„}\sigma_{qN}\text{"} \, \rho(b)} ;$$

In my work (H.J.P & P. Chiappetta NP B 291 (1987) 765)

Q^2-dependence cancels in $\langle p_\perp^2 \rangle_0$ and $\frac{1}{\sigma_{qN}}$.

Typical $\lambda \approx 20$ fm; $\langle p_\perp^2 \rangle \approx 1 \, \text{GeV}^2$

$$E_{loss}(R_A) = \frac{3}{\pi^2} \int_0^{R_A} \langle p_\perp^2 \rangle_0 \frac{z}{\lambda} \, dz$$

$$\approx \frac{3}{\pi^2} \langle p_\perp^2 \rangle_0 \frac{1}{2} \frac{R_A^2}{\lambda} ;$$

Landau Pom. (1953)

(Zakharov JETP Lett. 63 (1996) 952
Baier, Dokshitzer, Müller, Peigné, Schiff 96 04327 hep-ph)

Compare string energy loss & induced radiation:

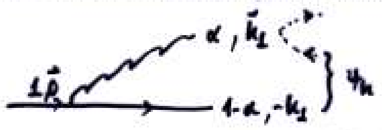
mean traversal length: R_A ($2R_A$)

	String loss	Rad. loss
N^{14}	2.7 GeV	0.3 GeV
	5.4 GeV	1.2 GeV
Pb^{208}	6.5 GeV	1.7 GeV
	13 GeV	6.8 GeV

Can one measure $\langle \vec{p}_\perp^2 \rangle$?

Gluon - Bremsstrahlung model : B. Kopeliovich & J. Nemchik (96)

The radiation of a gluon takes the time



$$t_r \approx \frac{2\nu}{k_T^2}\alpha(1-\alpha) \, .$$

The result

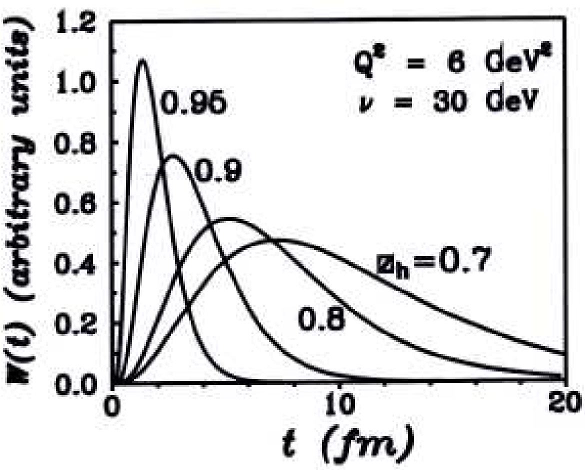
projection leads to the fragmentation function of the quark into the hadron, which rea

$$D(z_h) = \int_0^\infty dt W(t, \nu, z_h) \, ,$$

e $W(t, \nu, z_h)$ is a distribution function of the leading hadrons over the production time

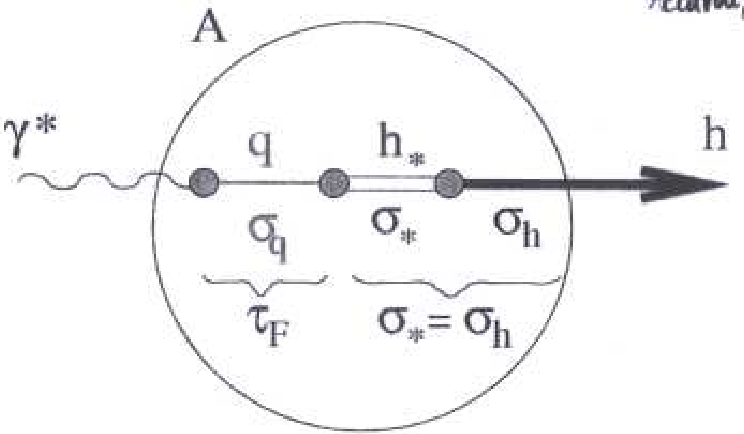
$$W(t,\nu,z_h) \;\propto\; \int_0^1 \frac{d\alpha}{\alpha}\, \delta\left[\alpha - 2\left(1 - \frac{z_h \nu}{E_q(t)}\right)\right] \int \frac{dk_T^2}{k_T^2}\, \delta\left[k_T^2 - \frac{2\nu}{t}\alpha(1-\alpha)\right] \times$$
$$\int dl_t^2\, \delta\left[l_T^2 - \frac{9}{16}k_T^2\right] \int_0^1 d\beta \delta\left[\beta - \frac{\alpha}{2-\alpha}\right] |\Psi_h(\beta, l_T)|^2 \, .$$

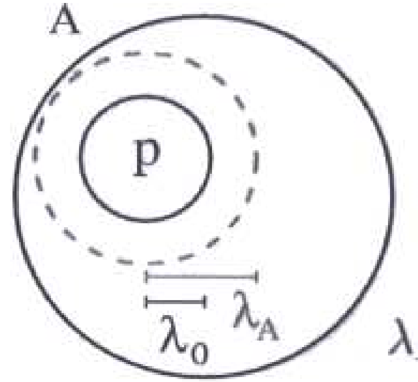
the quark energy $E_q(t) = \nu - \Delta E_{rad}(t)$. We have chosen a hadronic wave function ight-cone representation which satisfies the Regge end-point behaviour, $|\Psi_h(l_T^2, \beta)|^2$ $\sqrt{1-\beta}(1 + l_T^2 r_h^2/6)^{-1}$, where r_h is the charge radius of the hadron.



Nuclear absorption & rescaling of FF's

Accardi, Muccifora, Pirner (03)





$\lambda_A > \lambda_0$

nucl. abs. factor = probability of exiting from the nucleus:

$$\boxed{\mathcal{N}_A = \int d^2b \int_{-\infty}^{\infty} dy\, \rho_A(b,y) \left[S_A(b,y)\right]^{A-1}}$$

$$S_A(b,y) = 1 - \sigma_h \int_y^{\infty} dy'\, P_h(y'-y)\rho_A(b,y')$$

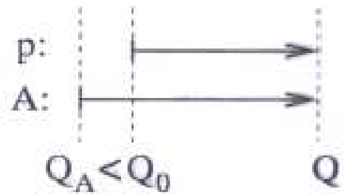
prob. that h is formed at y'-y from interaction point:

$$P_h(y'-y) = \left(1 - e^{-(y'-y)/\langle t_F \rangle}\right)$$

Change of confinement scale in A:

$$\lambda_0 Q_0 = \lambda_A Q_A$$

Q0 = start of DGLAP evolution



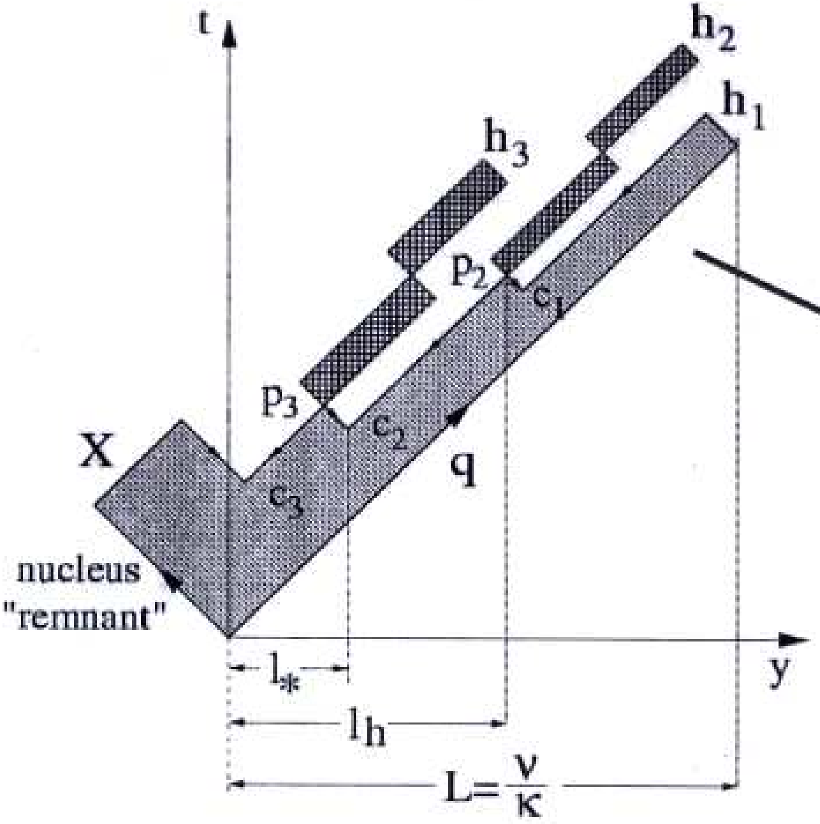
$\xi_A(Kr) = 1.36$

$$q_f^A(x,Q) = q_f(x, \xi_A(Q)Q)$$

$$D_f^{h|A}(z,Q) = D_f^h(x, \xi_A(Q)Q)$$

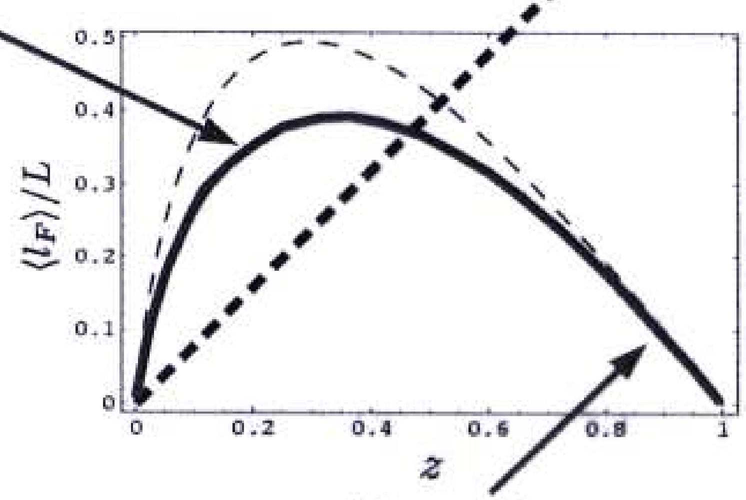
LUND string model & formation times

A. Bialas & M. Gyulassi (1987)



Lorentz dilatation of rest-frame form. time:

$$\tau_F = \underbrace{\frac{z_h \nu}{m_h}}_{\gamma} \tau_0 \propto z_h \nu$$

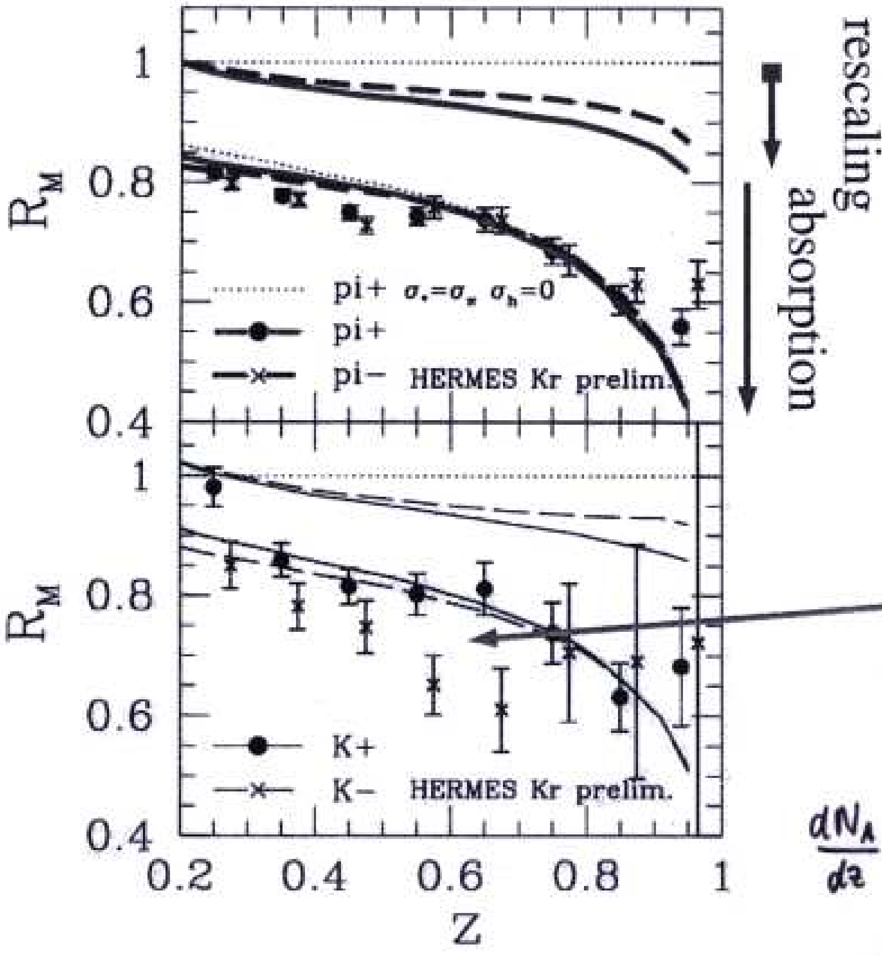


$\propto (1 - z_h)\nu$

see also Kopeliovich et al. '96 + recent talks
Airapetian et al. (HERMES) '01

Model vs. HERMES data

A.A, Muccifora, Pirner '03



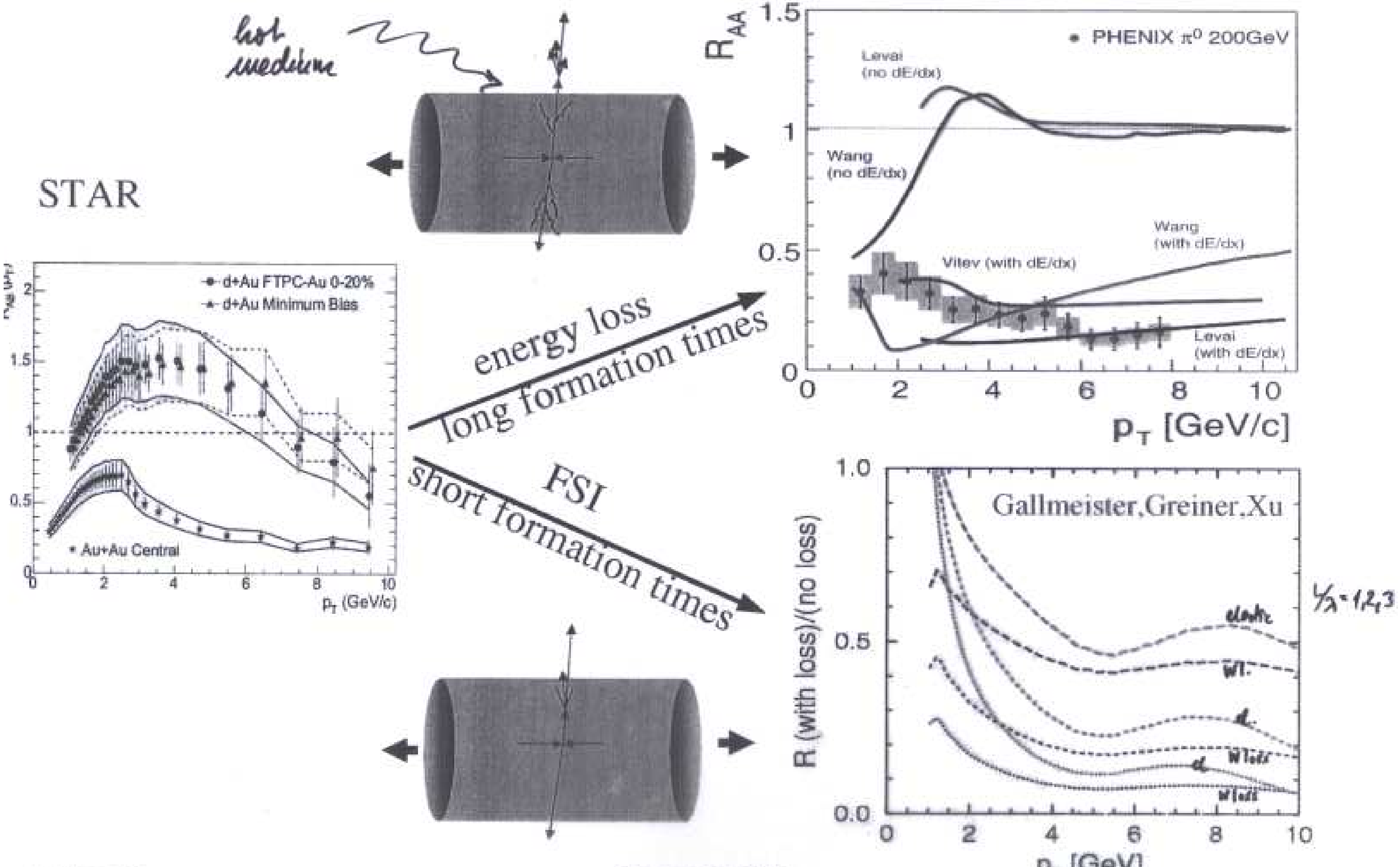
- two-step hadronization
- $\sigma_q = 0 \quad \sigma_* = \sigma_h$
- $\tau_F \propto (1 - z_h)\nu$

free parameter:
"string tension k"

K⁻ overestimated: ($\bar{u}$s not valence quarks of proton ⇒
shorter form. time $\tau_f(K^-) < \tau_f(K^+)$
(or σ_* - less natural) no fast generation

$$\frac{dN_A}{dz}\frac{1}{N_A} = \frac{1}{\sigma^{eA}} \int_{\text{Acceptance}} dx\, d\nu \sum e_f^2 q_f (x, \zeta_A Q^2) \frac{d\sigma^{eq}}{dx\, d\nu} D_f^h (z, \zeta_A Q^2) \cdot \mathcal{N}_A(z,\nu)$$

Parton energy loss or final state interactions (FSI)?



Conclusions

- HERMES data have good precision for detailed study
- Formation times and assumptions vary strongly from model to model
- Both absorption and energy-loss models account for data

How to decide?

- K- production
- A systematics
  (D, N, Ne, Kr data available - Xe planned at HERMES: A=2-131)
- Study observables different for absorption and en. loss

  Lessons from heavy-ions: Cronin effect?

  Two-particle azimuthal correlations?